

# Development of an Autonomous Aerial Reconnaissance System at Georgia Tech

Alison A. Proctor, Suresh K. Kannan, Chris Raabe,  
Henrik B. Christophersen and Eric N. Johnson

*UAV Laboratory  
School of Aerospace Engineering  
Georgia Institute of Technology*

## **Abstract**

The Georgia Tech aerial robotics team has developed a system to compete in the International Aerial Robotics Competition, organized by the Association for Unmanned Vehicle Systems, International. The team is a multi-disciplinary group of students who have developed a multi-year strategy to complete all levels and the overall mission. The approach taken to achieve the objectives of the required missions has evolved to incorporate new ideas and lessons learned. This document summarizes the approach taken, the current status of the project, and the design of the components and subsystems.

## **1 Introduction**

This paper describes Georgia Tech's entry to the 2003 Aerial Robotics Competition. The teams past accomplishments in the context of the current mission scenario include successful completion of the Level 1 requirements (Way Point Navigation) using a fixed wing aircraft in the year 2001. In 2002, the primary vehicle was changed to Georgia Tech UavLab's GTMax rotorcraft. Almost all aspects of Level 2 (identification of open windows and correct buildings) were accomplished including the mapping of building locations and open windows. However, the building associated with the IARC symbol was misidentified by a few feet. The GTMax provides the team with a robust autonomous flight platform capable of way point navigation, precision hover, high-speed flight and auto takeoff and landing. Additionally, the image processing system developed for Level 2 in 2002 has been overhauled to robustly identify buildings and windows. An important factor contributing to the misidentification of the building during the previous attempt at Level 2 was camera limitations. The camera used during Level 2 did not possess any zoom capabilities, and, with the helicopter flying at the minimum safe distance from the buildings, the resolution of the camera was not sufficient to accurately identify and locate the symbol. This problem has been alleviated by using a camera with optical zoom.

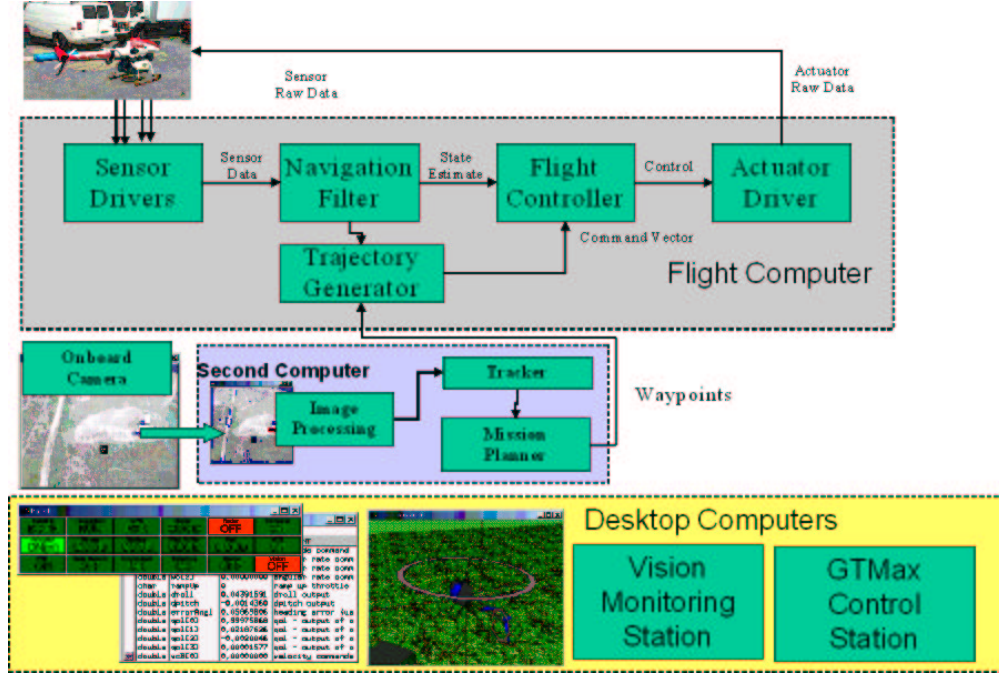


Figure 1: System Overview

## 2 System Overview

The overall reconnaissance system consists of 4 major components:

1. The GTMax helicopter from the Georgia Tech UavLab
2. The Image Processing Subsystem
3. Mission Planning and Object Tracking
4. Subvehicle

A diagram showing the interaction between the different components is shown in Figure 1. The GTMax helicopter is the primary air vehicle and is used during all parts of the mission. It is capable of full autonomous flight and may be commanded using waypoints. The GTMax carries two computers in addition to inertial and other sensors. The primary flight computer (PFC) runs the guidance, navigation and control algorithms which use waypoints that maybe uploaded over the network from a Ground Station (GS) or from any other computer on the network. The secondary flight computer (SFC) is normally used at the UavLab to fly experimental flight control algorithms. For the aerial robotics mission, the SFC will run the image processing, object tracking and mission planning routines. Hence, once activated the entire system is autonomous with onboard processing for all aspects of the mission. A ground station need only be used to view the progress of the mission and monitor telemetry.

The primary interface to the system is via the ground station computer which is a single notebook computer running OpenGL based visualization and telemetry software. The GS is also used for all vehicle modelling, simulation, controller development and hardware in the loop testing[2]. All flight critical software such as the guidance, navigation and control

algorithms are written primarily in C code and execute on the PFC. A pan-tilt network camera with zoom is available on board and is used as input to the image processor. A summary of the mission logic is provided below

- Given a search origin, plan a waypoint list in order to map the area
- During the mapping phase, the image processor returns candidate shapes while the object tracker improves position estimate of the shape over time.
- Visit each candidate building and use a matching filter to look for the IARC symbol, keeping track of the position with the tracker.
- Complete a detailed search of the correct building looking for portals.
- *Hover at the best opening and launch the probe to begin level 3*

All aspects of the technology are mature and work reliably except for the last item that includes inserting the probe into the building. This final aspect of the system is currently under development for the Level 4 mission.

## Safety

The GTMax has multiple features that provide various levels of safety. A few of those are discussed here.

- During any point in the mission the operator at the ground station may press a *Trajectory Stop* button which puts the helicopter immediately into hover. The mission may be resumed from this point without having to restart.
- At any point in the mission the safety pilot may take over manual control of the vehicle.
- A novel safety feature is the ability of the ground station operator to take over direct control of the helicopter and fly it using a joystick or mouse. This feature is critical in situations when the pilots radio link has failed. This feature is implemented through the wireless modem link which generally has a higher range of operation than the pilots radio.
- The final safety feature is the Kill Switch as required by the competition rules.

## 3 Primary Vehicle and Avionics

The primary air vehicle is based on a Yamaha R-Max helicopter. The GTMax helicopter weighs about 128 lbs (empty) and has a main rotor radius of 5.05ft. Nominal rotor speed is 700 revolutions per minute. Its practical payload capability is about 66 lbs with flight endurance of greater than 60 minutes.

### 3.1 Avionics

Figure 2 shows the airframe and associated avionics box. The avionics bay is modular and hosts sensors and computing hardware including,

- Flight Computer - *Embedded 233 MHz Pentium PC-104 SBC, 8 RS-232 ports, Ethernet, Flash Drive*

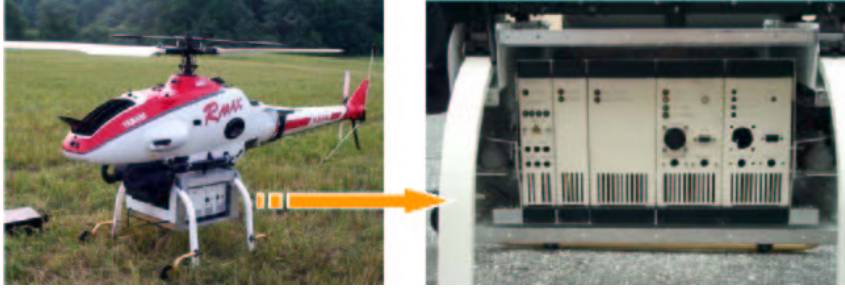


Figure 2: GTMax Airframe and Avionics Box

- Sensors - *Inertial Measurement Unit, Novatel D-GPS, Magnetometer, Sonar Altimeter, Vehicle Telemetry (RPM, Voltage, Pilot Inputs)*
- Data Links - *11 Mbps Ethernet Data Link, RS-232 Serial Data Link*
- Mission Payload - *Embedded 833 MHz Pentium 4 PC-104 SBC, Axis Video Server, Axis Web Camera*

The main avionics rack is shock mounted onto the helicopter. Each module has self-contained power regulation and EMI shielding. The overall architecture of the primary air vehicle avionics is shown in Figure 5. A particular advantage of this platform is that it is equipped with an onboard generator, which can provide for all power requirements onboard. Thus, the flight endurance of the helicopter is only limited by the amount of onboard fuel the vehicle can carry.

### 3.2 Control, Guidance and Navigation

A summary of the Navigation and Control Functions is illustrated in Figure 3.

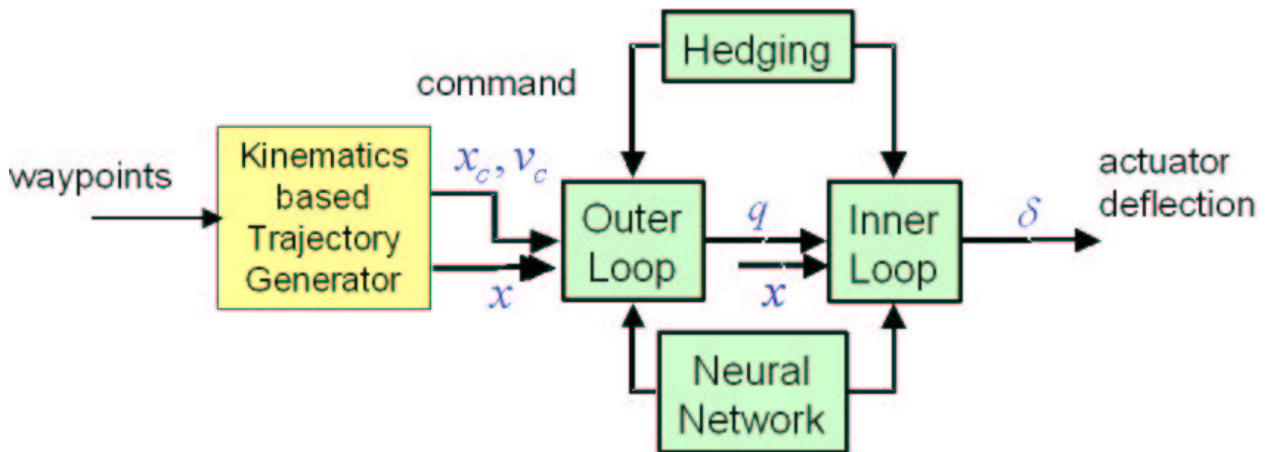


Figure 3: Control Architecture

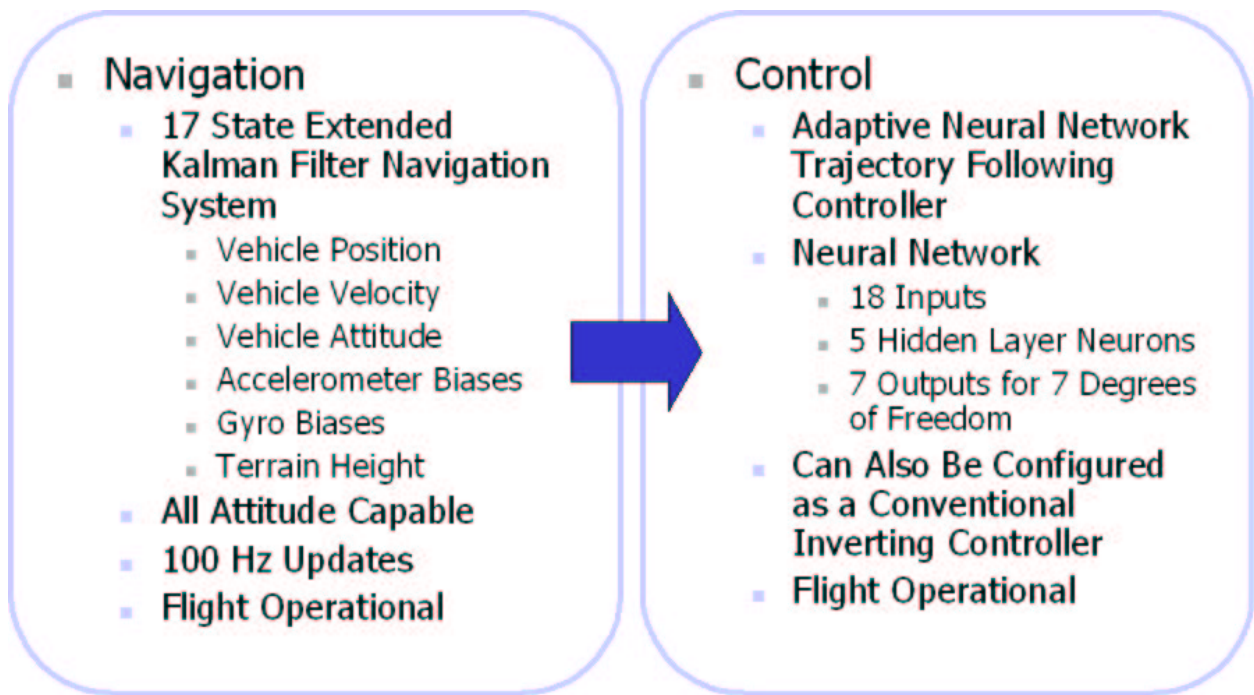


Figure 4: Navigation and Control

### Trajectory Generator

Commands to the helicopter take the form of different types of waypoints. All trajectories generated are assumed to be physically feasible by the helicopter. The kinematic model used for trajectory generation uses specifiable limits on the maximum speed and acceleration the aircraft may have during a maneuver. The various kinds of maneuvers are summarized below.

- CUT - takes three waypoints and generates a position and velocity profile that includes a turn to go from waypoint 1 to waypoint 3. The trajectory does not pass through waypoint 2.
- THRU - the trajectory will pass through the given waypoint without stopping
- STOPAT - the trajectory will end at the waypoint and bring the speed of the helicopter to 0.
- LAND - the trajectory will end at the given north, east position with commanded altitude being 0. This includes a slow descent until landing

### Navigation and Control

The flight controller takes smooth bounded position, velocity and attitude commands (heading) as inputs; details of the controller may be found in [1]. The navigation functions are performed at 100Hz and are based on the update rate of the IMU, which is used to trigger

navigation and control calculations on the PFC. The interaction between the navigation and control modules is shown in Figure 4.

All sensor output is collected via serial connection. This required adding a serial port expansion card (RS-232), resulting in a total of 8 serial ports on the PFC. Additionally, the actuator commands are sent to the helicopter via an RS-232 interface, which forms the primary interface to the physical vehicle. The navigation system consists of a 17 State Kalman filter that outputs a consolidated state vector of the vehicle to memory. This is then used by the flight controller for control calculations.

The flight controller consists of an outerloop and an innerloop. The innerloop performs attitude tracking and generates the required actuator deflections. The outerloop is used to generate the attitude quaternion ' $q$ ', required to follow a commanded translational trajectory given by denoting desired position and velocity. The controllers themselves are based on feedback linearization through dynamic inversion of a linear model of the helicopter in hover. The state feedback is denoted by ' $x$ '. The Neural Network is used to correct for any inaccuracies in the dynamic inversion. It is through adaptation in the neural network that the problem of flight control at different flight conditions (such as high speed flight) is addressed. Finally, the hedging block is used to protect the neural network from actuator saturation or other known nonlinearities to which we do not want adaptation to occur. However, due to significant time-delay the bandwidth of the closed loop system is limited. Time delay is handled using an integrated Smith predictor, which is described in [3], and has allowed an increase of position tracking bandwidth up to 2.5 rad/s.

## 4 Sub-vehicle

The sub-vehicle is a ground based robot carried in a launcher aboard the GTMax. The sub-vehicle carries a minimal set of distance measuring sensors and a video camera which are used for navigation and image acquisition. The exact configuration of the sub-vehicle and its navigation and communication systems are still under development.

## 5 Level 2

The Level 2 mission requirements are to use an autonomous aerial vehicle to locate a building with an identifying symbol within a designated search area. Once the correct building is identified, an opening in the building must be found, through which the third level of the mission could be commenced. The GTMax configuration chosen to complete the Level 2 mission is shown in Figure 1. The PFC runs the GN&C algorithms and the SFC runs the image processing algorithms, the object tracker and generates the flight path. The mission progress is monitored on two ground station computers. The GTMax Control Station interfaces with the primary flight computer and displays vehicle information, the object tracker information, and the flight plans generated by the mission planner. The Vision Monitoring Station receives streaming video from the camera as well as results from image processor. This allows the operator to monitor the efficiency of the image processing as well as visually document the results of the search in the final phase of the Level 2 mission.

## 5.1 Image Processing and Object Tracker

In order to complete the Level 2 mission, the vision system on the primary air vehicle needs to track and locate buildings and the open portals. The mission is broken up into three phases. The first phase is to map the buildings. This is done from a high altitude with the camera pointed straight down at the ground. The image processor scans each image for closed polygon contours. The vertexes of the polygons are recorded and passed to the tracker. The tracker converts the pixel location of the vertexes into local geographical coordinates using the state estimate from the GN&C. The tracker then reduces the vertexes into a characteristic four sided polygon. The polygon is then passed through a cascade of filters to determine the probability that it is a valid building. The tracker keeps a list of objects with the highest probabilities of being buildings, and transmits the results to the GS for display.

Once all of the buildings are mapped, a lower altitude sweep of the area is preformed to try and locate the symbol. For this portion of the mission the camera must be moved to obtain imagery of the top and sides of the buildings. The symbol is identified using a pattern matching technique. Once the symbol is located, the tracker determines which building it is located on. Then that building is circled in a low altitude flight looking for open portals. The portals are then classified and the most suitable opening is chosen.

## 5.2 Mission Management

For the Level 2 mission, the mission planner needs to monitor the progress and determine a flight plan required to complete the mission. The first task is to initiate a predetermined search pattern over the search area to look for buildings. After all of the buildings are mapped with adequate precision, the second phase of the search is initiated at a lower altitude. In addition to planning the trajectory of the helicopter, camera direction and zoom must also be chosen. During this phase the mission planner needs to ensure that each building is visited to look for the symbol. Once the correct building is located a flight plan to search for portals must be generated. This includes the flight path to the building and a portal search pattern. Once the most suitable opening is determined, the final phase of the Level 2 mission is to plan an approach to the portal, to put the primary vehicle in position to launch a sub-vehicle into the structure.

## 6 Level 3

The Level 3 mission requires the collection of visual information from within a building structure. An autonomous vehicle must be able to navigate inside the building, capture images of desired objects and transmit these images to monitoring personnel at the launch site up to 3 km away.

The strategy for Level 3 is to launch a ground based robot through the portal discovered by the primary vehicle. The robot will communicate with the primary vehicle from inside the structure and send imagery back to the GS.

## 6.1 Sub-vehicle Navigation and Communication

The sub-vehicle needs to be able to navigate with a certain amount of precision in the structure. The primary task of the vehicle is to transmit images of the entire internal structure to the GS in order to ensure that the correct information is passed. Therefore, although the vehicle does not have to know where it is, it needs to know that each room has been properly scanned and if there are any adjoining rooms.

The sub-vehicle is equipped with an array of distance measuring sensors and a video camera, whose images can be used for transmission and navigation. The data is analyzed to determine openings to adjoining rooms and for planning the path of the vehicle. The images from the sub-vehicle will then be relayed back to the GS.

## 6.2 Mission Planning

The Level 3 mission begins with the sub-vehicle in flight 10m away from the chosen portal. Upon landing in the room the sub-vehicle must be able to orient itself and begin transmitting back to the primary vehicle.

The robot is not expected to open (or move) doors, but should be able to move wherever humans normally move, including over doorsteps and up/down short flights of stairs. It also needs to be able to plan its trajectory intelligently so as to avoid becoming stuck under or between objects inside the building. The robot needs to keep track of openings and ensure that each one is visited to check for adjoining rooms. However, the robot should not exit the building through doors or windows once it has entered. This means that the robot must be able to determine the difference between an adjoining room and the outside. Route planning must be done dynamically to ensure that all openings, which may have previously been obstructed from view, are visited.

## 7 Conclusions

The Georgia Tech aerial robotics team has developed a multi-year approach to complete all levels of the International Aerial Robotics Competition mission. The program approach is flexible enough to allow lessons learned to be incorporated into the design as the project moves forward. Improvements in the GTMax avionics has allowed work on the level 2 and 3 missions to proceed unobstructed. The additional camera control and image processing capabilities interface with the mission planning and GN&C modules in order more efficiently detect relevant features and command the helicopter.

## 8 Acknowledgements

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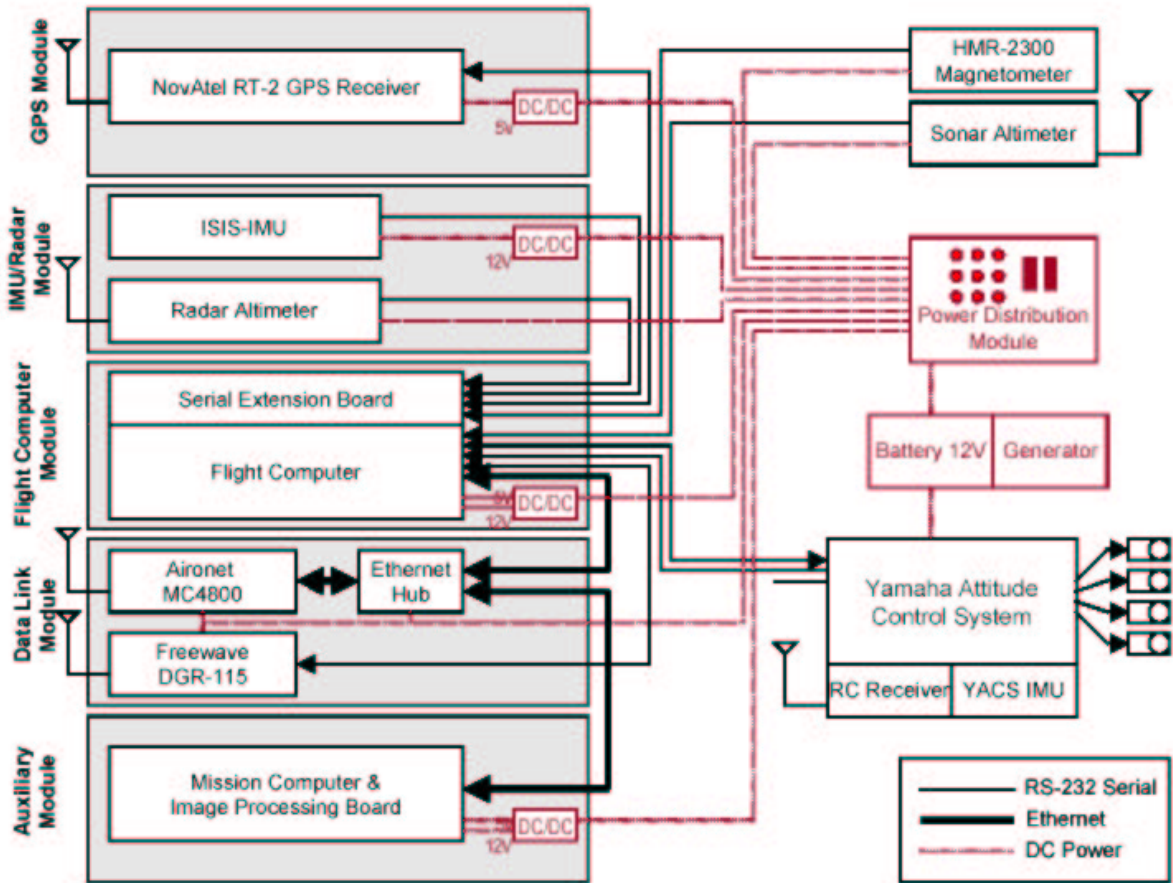


Figure 5: GTMax Schematic of Avionics Box